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GETTING DIRTY: TESTING C-17 AIRFIELD PERFORMANCE IN DIRT AND MUD LANDING ZONES

MAJ AARON A. TUCKER
MAJ CHRISTOPHER E. CHILDRESS
LT COL ROBERT J. POREMSKI

AIR FORCE FLIGHT TEST CENTER
EDWARDS AFB, CA

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14. ABSTRACT Operational C-17 aircrew are tasked continually with direct delivery of critical combat equipment and supplies. The Semi-Prepared Runway Operations (SPRO) testing was a joint Air Force Flight Test Center/Army Engineering Research and Development Center effort to expand airfield performance data to include a large part of the world's soil types, wet soil conditions, and a sizable increase in the allowable landing gross weight. Five landing zones were constructed around the United States in various soil types. A C-17 was instrumented for structural loads and performance measurements and modified to operate in dirt and mud. After extensive test and safety planning, site preparation, and aircrew training, the test team began to expand the C-17 SPRO capabilities through a build-up/down approach in gross weight/RCR at each runway, in sequence. The complexity of test support at multiple, deployed locations, large uncertainty in aircraft performance and landing zone response, and specific weather requirements were continual challenges for the test team. Extensive planning, a deliberate build-up approach, and extreme operational flexibility were validated as keys to success for this flight test program. The immediate, distinct advances that this flight test program provide to the operational mobility crews defines successful military flight test in the current age.					
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Getting Dirty: Testing C-17 Airfield Performance in Dirt and Mud Landing Zones

Major Aaron A. Tucker¹

Major Christopher E. Childress²

Lieutenant Colonel Robert J. Poremski³

United States Air Force, Edwards AFB CA 93524

Operational C-17 aircrew are tasked continually with direct delivery of critical combat equipment and supplies in the course of their global airlift mission. Some ground units were supported only by semi-prepared (graded, compacted dirt) landing zones. The C-17 Semi-Prepared and Aluminum Matted (SPAM) flight test program in 1997 produced performance data for approximately one-sixth of the world's soil types and no data were available to support wet landing zone takeoff and landing performance. The Semi-Prepared Runway Operations (SPRO) testing was a joint Air Force Flight Test Center/Army Engineering Research and Development Center effort to expand airfield performance data to include a large part of the world's soil types, wet soil conditions down to icy-equivalent runway condition readings (RCR), and a sizable increase in the allowable landing gross weight. Further, data were collected on landing zone degradation rates to support logistics planning for U.S. Army support. Five landing zones were constructed around the United States in various soil types. A C-17 was instrumented for structural loads and performance measurements and modified to operate in dirt and mud. After extensive test and safety planning, site preparation, and aircrew training, the test team began to expand the C-17 SPRO capabilities through a build-up/down approach in gross weight/RCR at each runway, in sequence. Although some test points were quite challenging to execute safely, all test objectives were met and the necessary data to evaluate the C-17 performance at all gross weights and RCRs was obtained. The complexity of test support at multiple, deployed locations, large uncertainty in aircraft performance and landing zone response, and specific weather requirements were continual challenges for the test team. Extensive planning, a deliberate build-up approach, and extreme operational flexibility were validated as keys to success for this flight test program. The immediate, distinct advances that this flight test program provide to the operational mobility crews and their supported ground combat units defines successful military flight test in the current age.

Nomenclature

μ	=	coefficient of friction
F_{brake}	=	force provided by aircraft brakes
W	=	aircraft weight
L	=	aircraft lift
D	=	aircraft aerodynamic drag
β	=	runway slope
F_e	=	net engine thrust
m	=	aircraft mass
a_x	=	inertial acceleration along the aircraft's longitudinal axis

¹ C-17 Experimental Test Pilot, 418 FLTS/DOO, 35 N Flight Line Rd, Edwards AFB CA 93524, Senior Member.

² C-17 Experimental Test Pilot, 418 FLTS/DOO, 35 N Flight Line Rd, Edwards AFB CA 93524.

³ C-17 Test Director, Global Reach Combined Test Force, 35 N Flight Line Rd, Edwards AFB CA 93524.

I. Introduction

THE C-17 Semi-prepared Runway Operations (SPRO) flight test program was designed to collect data on both aircraft performance and the durability of semi-prepared dirt landing zones (LZ) constructed in a variety of soil types under both dry and wet conditions. Previous tests on semi-prepared landing zones were all conducted in a single type of soil representing approximately one-sixth of the global soil types.¹ These data will be applied to world-wide air mobility operations to support the U.S. Army. One C-17A Globemaster III was instrumented to gather structural load, flight performance, and engine performance data. Five landing zones were built in different climactic conditions and soil types using various construction techniques: Fort Hunter-Liggett, California; Fort McCoy, Wisconsin; Fort Chaffee, Arkansas; and two sites on Rogers Dry Lakebed, Edwards Air Force Base (AFB), California. The data gathered from these locations represent a large part of the world's soil types.

The results of these tests represent specific military capabilities and will not be discussed. This report will focus on the experience of the test team and address the test overview, test item description, test methodology, qualitative data analysis, and lessons that the test team garnered from planning and execution.

II. Test Overview

The scope of the flight test program was particularly extensive, and the teamwork between disparate organizations not normally involved in flight test was noteworthy. The U.S. Army Engineering Research and Development Center (AERDC) was the designated responsible test organization tasked with building and maintaining the landing zones, collecting civil engineering data during execution, and producing a final, combined test report. The U.S. Air Force Civil Engineering Support Agency assisted AERDC with data collection. The 412th Test Wing, Air Force Flight Test Center (AFFTC), at Edwards AFB was a participating test organization responsible for test execution and providing an aircraft performance report. The executing test organization was the 418th Flight Test Squadron through the Global Reach Combined Test Force. A diverse force of active duty military, Department of Defense civilians, and contractor aircrew, engineers, maintainers, and program managers formed a deployed force of approximately 50 people and an equal number supporting the test execution from Edwards AFB and The Boeing Company factory in Long Beach, California. Additionally, host units from the U.S. Army Reserve, National Guard, and Air National Guard at each of the testing locations assisted with logistical and fire/rescue support during a typical, two-month period of execution. Finally, aerial port units deployed from Travis AFB and Channel Islands Air National Guard Base, California, with cargo handling and fueling support equipment, and Special Tactics Teams from Pope AFB, North Carolina, surveyed each landing zone for appropriate dimensions and obstacle clearance before test execution.

A. Air Force Flight Test Center Test Objectives

The overall test objective was to evaluate the takeoff and landing performance of the C-17A aircraft during SPRO on various soil types, climates, soil water contents, and landing zone deterioration states. Specific test objectives were enumerated:

- 1) Determine landing performance on dry and wet landing zones: determine runway condition reading (RCR), aircraft braking friction coefficient (μ), and landing distance across aircraft operating weights and RCR values.
- 2) Determine takeoff performance: determine aircraft runway friction factor (RFF) and takeoff distance. The RFF represents the force retarding an accelerating aircraft from rolling friction (dry concrete RFF=2), soil compression, rut/till impingement, etc. These forces are considered small relative to braking forces so are considered only in the takeoff case.
- 3) Evaluate directional controllability on wet landing zones: ensure that crews have the ability to maintain centerline without aerodynamic control authority.
- 4) Collect landing gear load data during SPRO: there was concern that structural loads may be limiting on a rutted landing zone.
- 5) Evaluate ground handling qualities during wet SPRO: operational crews must be able to accomplish minimum-radius taxi turns on small, austere landing zones.
- 6) Determine aircraft damage incurred during SPRO: operational experience indicated that rocks and dirt can damage vulnerable areas of the aircraft. Evolving complements of armor were developed and tested throughout the duration of the test program.
- 7) Collect baseline takeoff and landing performance data on a concrete runway: both RCR and RFF are referenced to concrete runways so the performance of the specific C-17 test aircraft was determined on concrete to compare to subsequent SPRO performance.

B. Army Engineering Research & Development Center Test Objectives

- 1) Measure soil shear strength: various soil types and construction methods were selected to represent global soil types.
- 2) Determine landing zone deterioration rate: evaluate the ability of the soil type and construction method to support US Army Strategic Brigade Airdrop Echelon B requirements.
- 3) Determine surface roughness during landing zone deterioration: each landing and takeoff event changes the characteristics of the landing zone.
- 4) Measure loose soil (till) generated during landing zone deterioration and attempt to correlate the amount of till to RFF.

III. Test Article Descriptions

Both the aircraft and the landing zones were considered test articles, the former provided by the Air Force Flight Test Center at Edwards AFB and the latter under the purview of the Army Engineering Research and Development Center in Vicksburg, Mississippi.

A. C-17A aircraft

The C-17A aircraft, United States Air Force aircraft serial number 03-3121, was used for this test. The C-17A aircraft is a long-range, heavy logistic transport aircraft powered by four Pratt & Whitney F117-PW-100 engines. Its design characteristics—high-lift wing, slats, externally blown flaps, and landing gear with high flotation tires—give it the capability to operate into and out of short runways and austere airfields while carrying large payloads. The engine thrust reverser system is capable of backing a fully loaded aircraft. Reverse thrust engine blast is directed forward of and above the wings, eliminating effects of wind blast on troops or equipment during engine running on/off-loading operations. For aircraft attitude/speed control with landing flaps extended, powered lift control technique is used. The main landing gear consists of two struts on each side with three wheels on each strut. A single strut and dual nosewheels make up the nose landing gear. The dimensions of the C-17A aircraft are shown in Fig. 1.²

The C-17A landing gear structural members were instrumented with strain gages in order to calculate landing gear and fuselage loads. These values were continuously monitored and analyzed after each landing or takeoff event in order to guard against exceeding structural load limits. Landing gear shock strut pressures, wheel speeds, brake pressures, and antiskid currents were recorded to calculate aircraft braking performance.³ Finally, aircraft operation, engine performance, and navigation parameters were recorded to complete the analysis.

The C-17A underwent further modifications designed to protect the aircraft from the punishing environment of a dirt and mud landing zone. As with operational C-17A aircraft, the lower anti-collision light was removed and replaced by an aluminum plate. Lower antennae also received protective covers. The underside of the fuselage and landing gear pods as well as the landing gear and tires are often damaged by sand and rocks during takeoff, landing, and taxi. Thin, high-density foam armor was developed and applied to vulnerable areas such as the leading edges of the main landing gear doors,

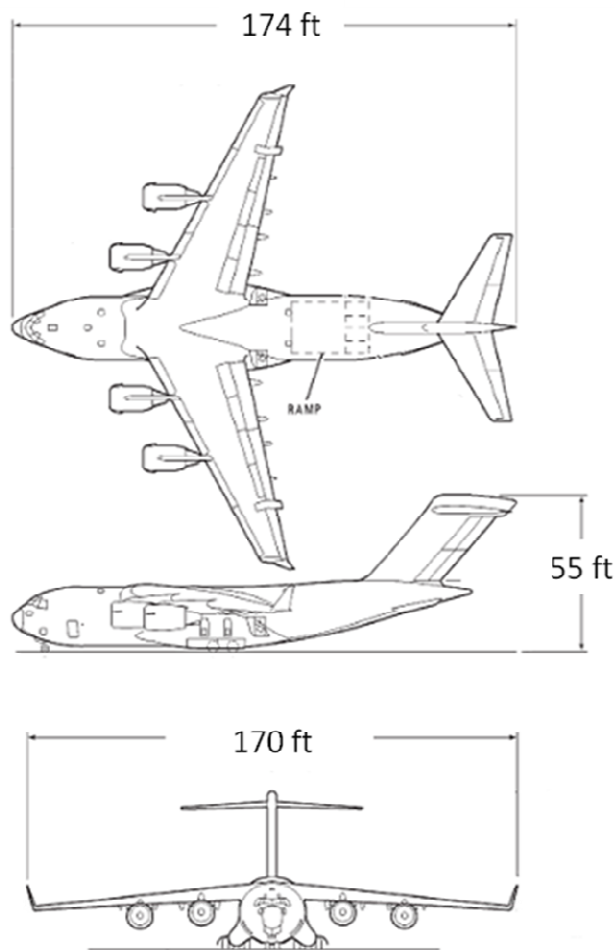


Figure 1. C-17A Globemaster III.

struts, and axles. Several iterations of improved armor were evaluated throughout the course of the SPRO test program.

B. Landing Zones

AERDC selected four locations to construct five landing zones based on soil type, climate conditions, and logistical considerations as shown in Table 1. The material properties of silty sand, low plasticity clay, and high plasticity clay had been characterized for load-bearing strength but not for aircraft landing and braking performance. These soils represent a large part of the world's soil types and met the requirement to generate data to support global mobility operations. The AERDC engaged different agencies to construct each landing zone. The U.S. Air Force REDHORSE, Army Corps of Engineers, and Navy Seabees each constructed landing zones to support C-17 operations.⁴ Special Tactics Teams based at Pope AFB, North Carolina, provided landing zone surveys specific to C-17 operations that included position data and arrival and departure obstacle clearance information.

A myriad of logistical considerations accompanied the site selection of each landing zone. Maintenance would have been very difficult on an austere landing zone, so a staging airfield was selected nearby. Fort Hunter Liggett and Edwards AFB landing zones were supported out of the Edwards AFB main runway. Operations at Fort Chaffee originated from the Air National Guard Base at the Fort Smith Regional Airport, and the Air National Guard Combat Readiness Training Center at Volk Field supported operations at Fort McCoy. Maintenance inspections, major repairs, servicing, and ballast adjustments were accomplished at the staging airfield each evening in preparation for the next day's testing. If the staging airfield was close, people drove between locations, which reduced the total number of deployed personnel. Fueling, cargo handling, and limited maintenance support was also located at the landing zone. Sufficient fire fighting and crash rescue were also required at each location.

Table 1. Test Sites.

	Location	Climate
1	Fort Hunter Liggett, CA	Semi-arid
2	Fort Chaffee, AR	Temperate
3	Fort McCoy, WI	Temperate
4	Edwards AFB, CA (Goatman LZ)	Temperate*
5	Edwards AFB, CA (Lakebed 25)	Semi-arid

*Rogers Dry Lakebed is a semi-arid climate so water was added to simulate soil in a temperate climate

IV. Test Methods

A. Test/Safety Planning

Any planning program starts with a review of previous efforts and their lessons learned. The test team reviewed previous C-17 test programs on semi-prepared landing zones including the 1997 Semi-Prepared and Aluminum Matted (SPAM) and 2000 SPAM II C-17 test programs.^{5,6} Individuals with experience in C-130 Hercules aircraft austere field operations were also available within the Global Reach Combined Test Force. Lessons learned included:

- 1) Engine foreign object damage (FOD) should be expected but can be mitigated by restricting thrust reverser operation to above 30 knots groundspeed (i.e., no backing operations).
- 2) Provide a prepared underrun in case an aircraft touches down short of the touchdown zone.
- 3) Maximum brake application to a full stop exacerbates rutting; use normal braking below 30 knots groundspeed.
- 4) Engine dust ingestion clogs environmental system filters; releasing brakes at 30 knots groundspeed allows the aircraft to taxi ahead of dust clouds generated on landing (Fig. 2).

These previous experiences helped to drive the design of the landing zones, the safety planning, and test procedures. A landing zone allows for a underrun, 500-ft touchdown zone, test section (dry



Figure 2. Wet Landing Zone at Fort McCoy.

or wet), dry stopping zone, and dry safety zone. The test section was not sufficient to accommodate a full-stop landing roll under wet conditions. During wet landing zone testing, the aircraft would exit the wet test section then complete the landing roll in the dry stopping zone. An additional dry safety zone was available but never planned or required. Two landing zones were located on the Rogers Dry Lakebed at Edwards AFB, California to allow for takeoff and landing performance testing at the heaviest aircraft weights.

Safety planning includes identifying hazards of equipment or personnel damage and seeking to mitigate or eliminate the threats. A general safety build-up approach was implemented that allowed the test team to gain experience with test procedures at familiar conditions before proceeding to areas of the performance envelope that are more uncertain.⁷ The first experience with a given landing zone would be light-weight on a dry runway condition reading (RCR approximately 23). The prescribed build-up approach increased the aircraft weight to medium- and heavy-weight testing on a dry landing zone before attempting wet testing and a decrease in RCR. Similarly, the aircraft weight would build up from light-weight to heavy-weight at a slightly reduced RCR (approximately 16) then repeating the process at RCR values of 12, 8, and 4 in turn. Lower RCRs are implemented by increasing the water added to the landing zone by AERDC water trucks; rain is not allowed to affect the landing zone surface condition. The test team would use experience gained at each step to refine predictions of the structural loads or controllability that would be experienced at the next point. Each of these steps would also be investigating progressive runway deterioration and increasing RFF through AERDC's data collection after each takeoff and landing (Fig. 3). AERDC's data requirements must also be met before progressing in weight or RCR.



Figure 3. Measuring Rut and Till at Fort McCoy.

The C-17 SPRO test team also identified five test-specific hazards and minimizing procedures:⁸

- 1) Loss of directional control during wet runway landings. The test team designed a task to evaluate the directional control handling qualities at 80 knots before attempting to land at a given RCR.
- 2) Overrunning the available runway. A dry safety zone was designated to mitigate this hazard.
- 3) Exceeding airframe structural limits. Instrumentation was provided that could monitor loads in real time and allow the test team to predict when landing zone deterioration was approaching a structural load limit.
- 4) Extended exposure to foreign object damage. Reverse thrust operations below 30 knots were restricted and maintenance inspections prescribed.
- 5) Mud falling from the aircraft after wet SPRO testing. Procedures required a departing aircrew to cycle the landing gear over the landing zone before flying back to the staging airfield (Fig. 4). There, airfield sweepers would ensure that taxiways were not contaminated with mud or debris.



Figure 4. Mud Hazard after Wet Landing Zone Test.

B. Test Team Training

Another method to mitigate risk is through test team training. Each member of the large team had procedures to develop, fine tune, and practice. Pilots became adept at precise aim point and airspeed control required to execute consistent assault landings within a 500-ft touchdown zone. Extensive, real-time instrumentation allowed engineers to give immediate feedback on touchdown point and time delay from touchdown to full actuation of brakes. These feedback were critical in minimizing the confounding factor of pilot technique. Engineers flew onboard and practiced reducing the data and calculating the resulting aircraft performance. Flight test engineers practiced

conducting the test, calculating takeoff and landing performance predictions, and recording and comparing the actual performance. These comparisons were critical in detecting deviations from predictions and safely continuing testing. Test conductors and aircraft commanders were able to establish a rhythm within their crews and understand each member's duties in order to more effectively orchestrate all of their activities. Strong leadership, exceptional professionalism and test discipline resulted in outstanding test efficiency and an overall safe operation.

Assault takeoffs and landings were practiced on concrete runways using SPRO procedures, and the entire test team was involved in the effort. Not only did the crew gain proficiency, but the extensive instrumentation modification was exercised to discover flaws in installation, recording, or data processing algorithms. More than a few problems were solved quickly and without impact to the test schedule because they were discovered before landing on a dirt landing zone with all the attendant support as described above. After confidence in the test team and instrumentation was established, pilots honed their assault landing skills on a narrow concrete landing zone used for training operational C-17 pilots. Finally, the test team performed practice assault landings on a Rogers Dry Lakebed runway as a readiness exercise for test and to give the test team experience with semi-prepared runway operations.

C. Data Analysis

Aircraft performance on concrete was critical to the analysis of SPRO performance data. No equipment was available to directly measure RCR and RFF on a dirt landing zone so the aircraft instrumentation, after calibration on a concrete runway with known RCR and RFF, became the truth source. In general, RCR is a measure of an aircraft's ability to brake to a stop on a given surface (e.g., RCR on dry concrete is 23 for the C-17A). Similarly, RFF is used to represent the retarding force experienced by free-rolling wheels in the takeoff case and is referenced to a dry concrete runway (i.e., RFF on dry concrete is 2). In order to calculate RCR, braking stopping performance was analytically referenced to equivalent braking performance on a concrete runway. The RFF was calculated by comparing test SPRO takeoff roll distances to RFF tables generated during the SPAM test program.⁹

The RCR and RFF are aircraft-specific and referenced to a concrete runway while μ is related to the landing surface's retarding force by Eq. 1 where F_{brake} is braking force, μ is the coefficient of friction, W is aircraft weight, L is aircraft lift, and β is the runway slope. The nose gear is free-rolling, and landing gear rolling friction is considered small compared to the braking force in included in F_{brake} .

$$F_{brake} = \mu(W \cos \beta - L) \quad (1)$$

The braking force is also expressed as the sum of forces acting on an aircraft on landing roll (Eq. 2) where F_e is the net engine thrust, D is aerodynamic drag, m is the aircraft mass, and a_x is the acceleration of the aircraft along the inertial x axis. F_e , D , and L are calculated using an analytical aerodynamic model of the C-17A. Weight, W , is calculated from aircraft weight and balance data, and a_x is recorded from the aircraft's onboard inertial reference units.

$$F_{brake} = F_e - D - W \sin \beta - ma_x \cos \beta \quad (2)$$

Thus, the coefficient of friction can be expressed in Eq. 3.

$$\mu = \frac{F_e - D - W \sin \beta - ma_x \cos \beta}{W \cos \beta - L} \quad (3)$$

Once RCR, RFF, and μ have been calculated via aircraft instrumentation, the results are correlated to data collected on the landing zone condition (e.g. rut, till, soil moisture content) as well as by a portable μ -meter towed behind a truck (Fig. 5). These correlations can be referenced in the field as the source for operational takeoff and landing data calculations. Actual data protects operational aircrews from overly-restrictive limits based on overly-conservative assumptions about SPRO aircraft performance and permits safer and more efficient operations.

V. Results and Discussion

The data and results from the SPRO takeoff and landing performance evaluation represent specific military capabilities. While each soil type responds in a unique manner to C-17A takeoff and landing events, these data will be valuable to global C-17 semi-prepared runway operations.



Figure 5. Portable μ -meter.

VI. Lessons Learned

The lessons learned from this testing is particularly valuable to those who might proceed with a test program characterized by extensive coordination with a multitude of agencies actively involved in the planning and test execution.

A. Extensive Planning

Extensive planning is a significant investment of time and money, but it educates the test team's judgment and enables good decisions to be made in a timely manner. Accurate, timely decisions are critical to the success of a flight test program, particularly when large teams of highly-specialized professionals are deployed to support the test effort. Seeking out and applying the lessons learned from previous test programs includes dedicating some time to visiting the technical library and accomplishing a review of literature. When deployed operations are required, site visits are crucial to understanding the unique challenges and opportunities available at the test site. Also, personal relationships with the host agency's leadership and support offices can be useful during execution during the near- and far-term test programs.

Risk management starts with planning and allows the test team to necessarily eliminate and mitigate many of the risks associated with flight test. Outside expertise can be utilized to review the test plan, gain another perspective, and gather new ideas on how to approach complicated test programs. However, some risks will remain and the leadership is entitled to be informed of the probable costs of executing important test programs. A build-up approach is a valuable tool to mitigate the risk of the unknown. Each step progressively brings the end state into focus with a clarity that is not possible from the outset. Each discipline represented within a test team, no matter how skilled and experienced, deserves the benefit of a build-up approach. Maintainers, engineers, and aircrew all deserve resources dedicated to their proficiency and training before carrying a test program toward the unexplored.

B. Deployed Operations

The complexity of a test program is magnified when the test team is uprooted from its normal support structure and planted in a new environment. Normal, daily tasks are difficult and communication requires careful attention to ensure that the myriad of players needed to support the test know the current plan which will constantly change. It is critical to understand the paperwork associated with moving the test team to a new operating location and working efficiently and effectively once in place. The costs of apparent conveniences show their value when utilized to keep a large, expensive operation moving. Minor considerations to the host unit (e.g., washing mud from the aircraft in an unobtrusive parking spot, keeping borrowed office space clean) earn goodwill capital that must be carefully preserved for when the team needs the inevitable favor.

C. Flexibility

Flexibility is born of careful planning, and allows the test team to aggressively push to take advantage of favorable conditions. The creativity and ingenuity of trusted team members can be the source of amazing problem-solving skills. The trust necessary to exercise those ideas, however, is rooted in rigorous test discipline and a commitment to do the right thing. Flexible test and safety plans give just enough structure to allow for test team judgment to complement test discipline. Overly-restrictive planning requires the approval of a new rule set when unexpected circumstances are encountered which are a certainty in a test program. Overly-permissive planning does not properly guide the test team's efforts and leads to miscommunication and wasted effort.

Also, weather requirements add an additional dimension to planning. Operations would come to a halt during adverse weather which wreaks havoc on a test schedule particularly on the personnel and equipment engaged to support the test effort. Plans were made, and contracts were signed well before any specific weather forecasts were available. Appropriate attention to realistic scheduling and test efficiency factors can utilize historic weather data to enable the development of realistic test schedules.

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